

Pseudo-vortices

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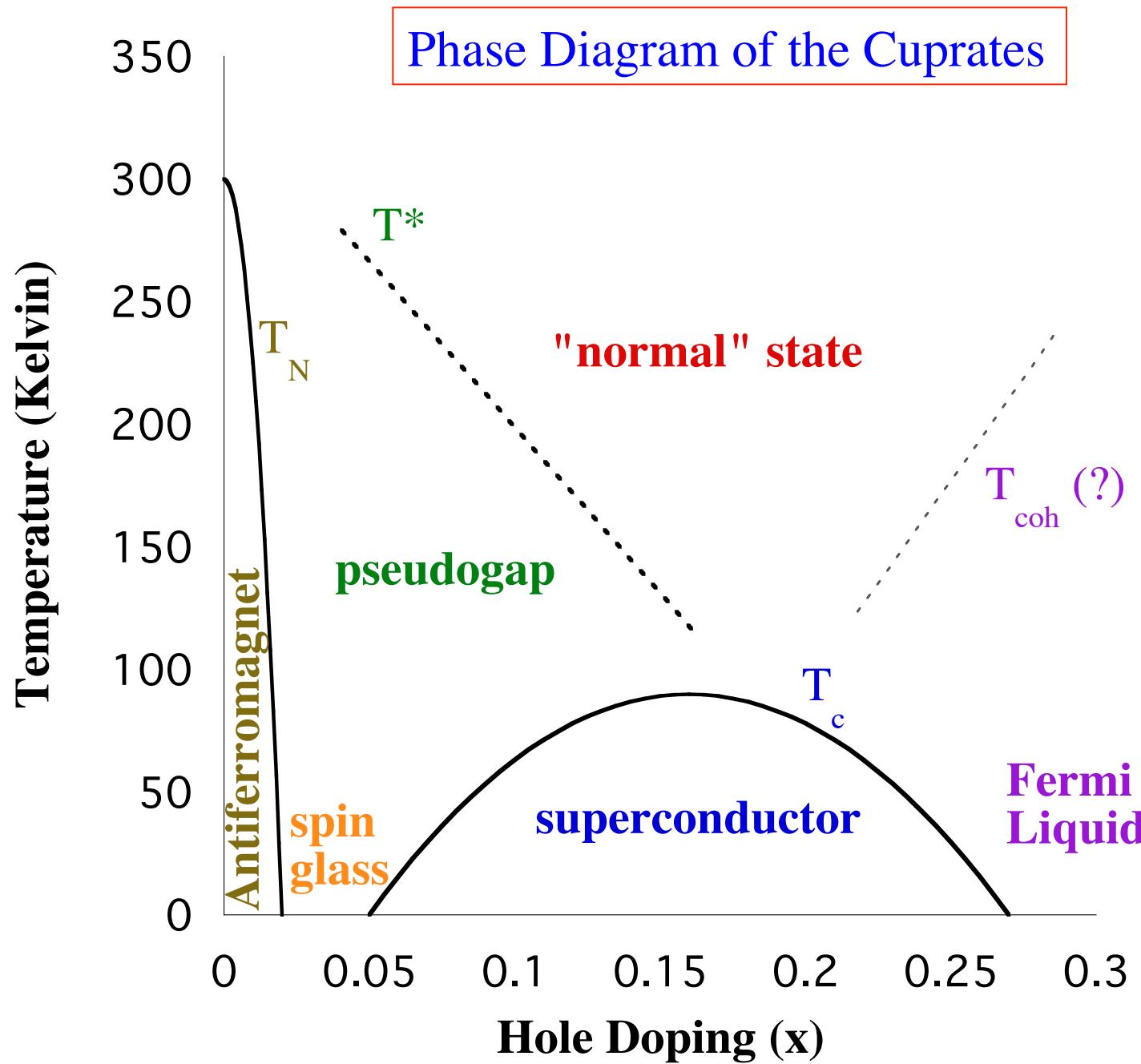
&

Center for Emergent Superconductivity

Alex Levchenko, Zoran Ristivojevic,
Victor Vakaryuk, Andrey Varlamov



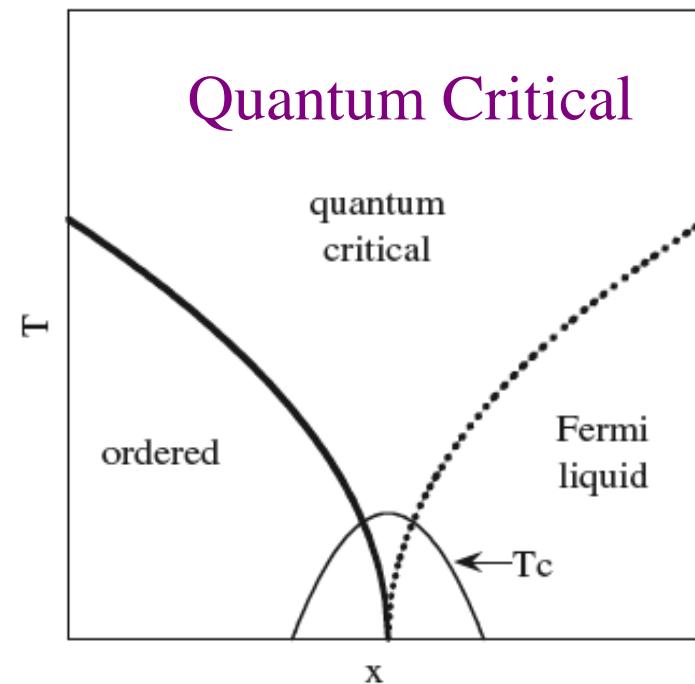
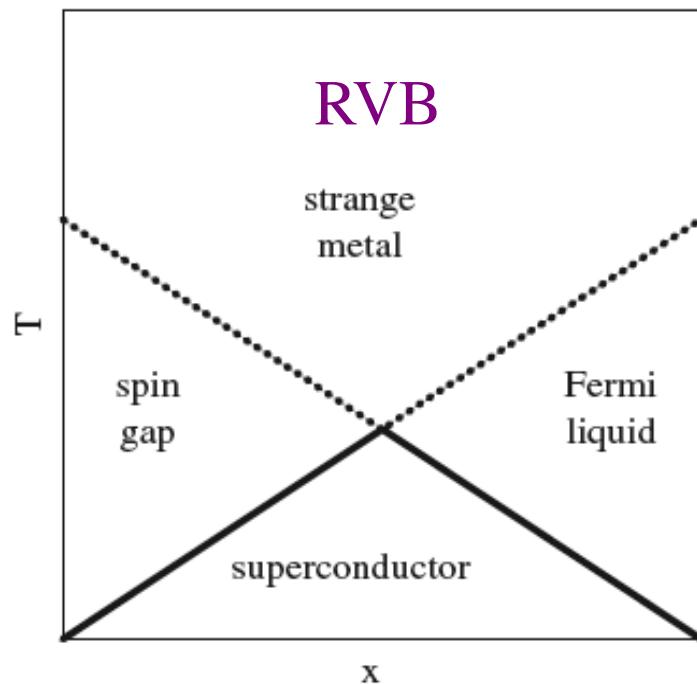
NHMFL - Oct. 21, 2011



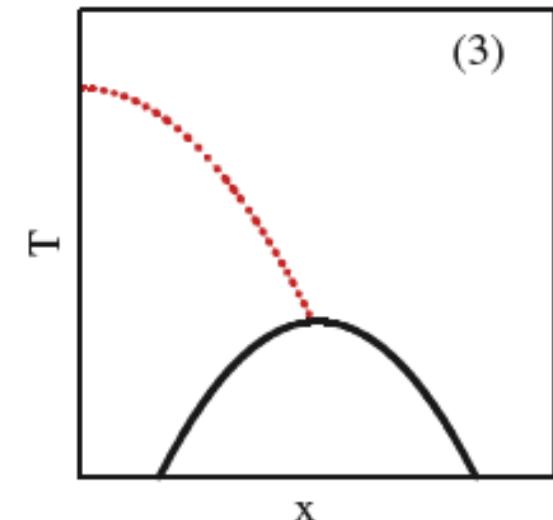
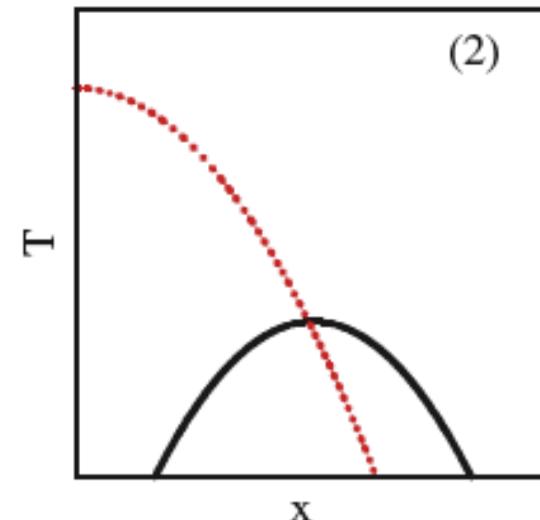
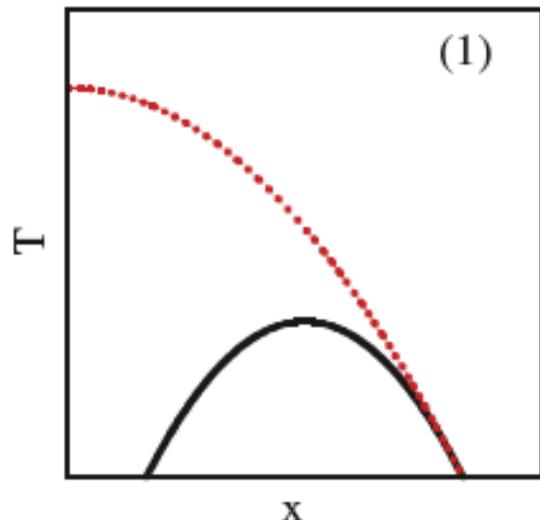
What is the Pseudogap?

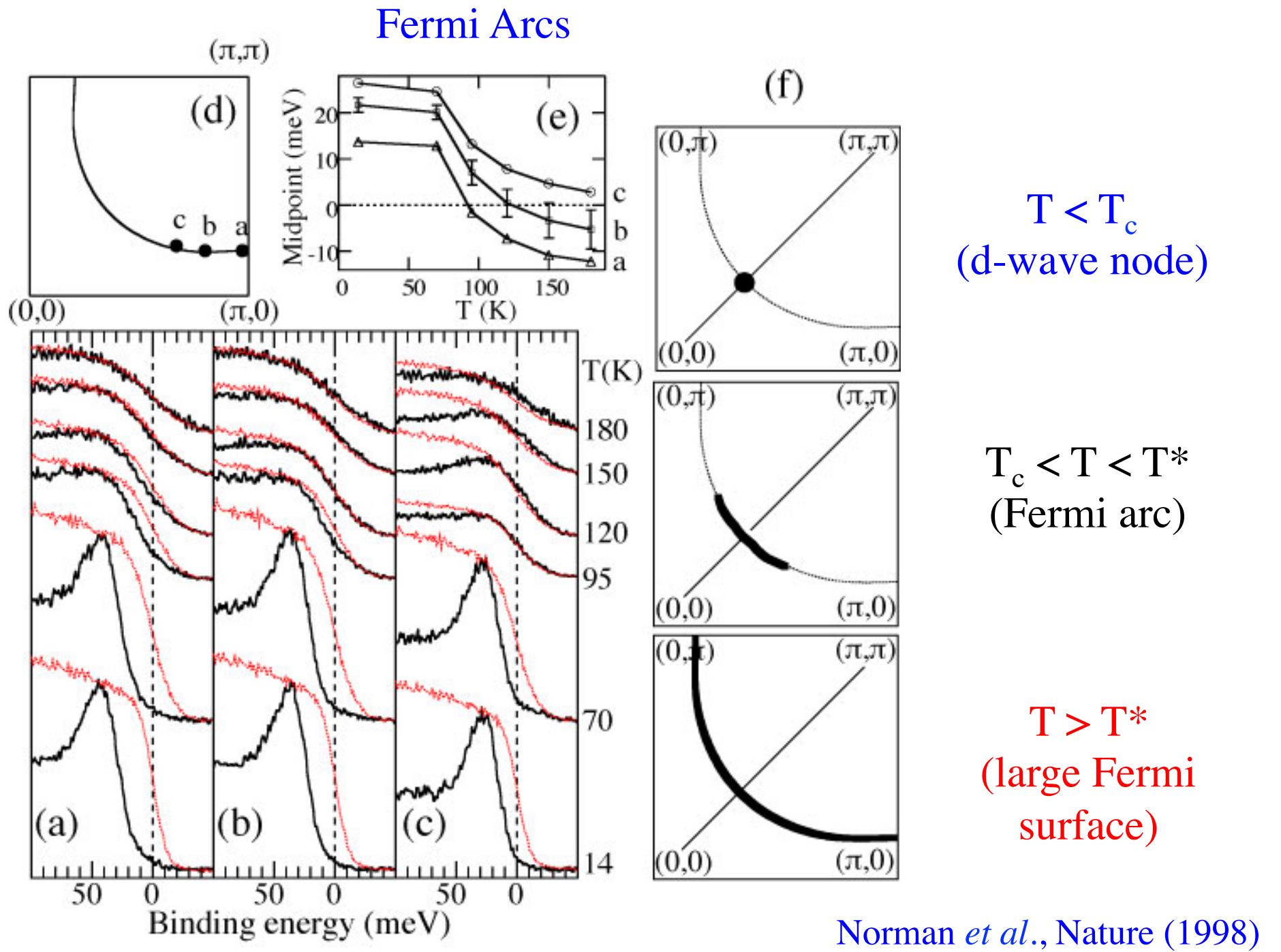
1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

Two Theories of the Phase Diagram

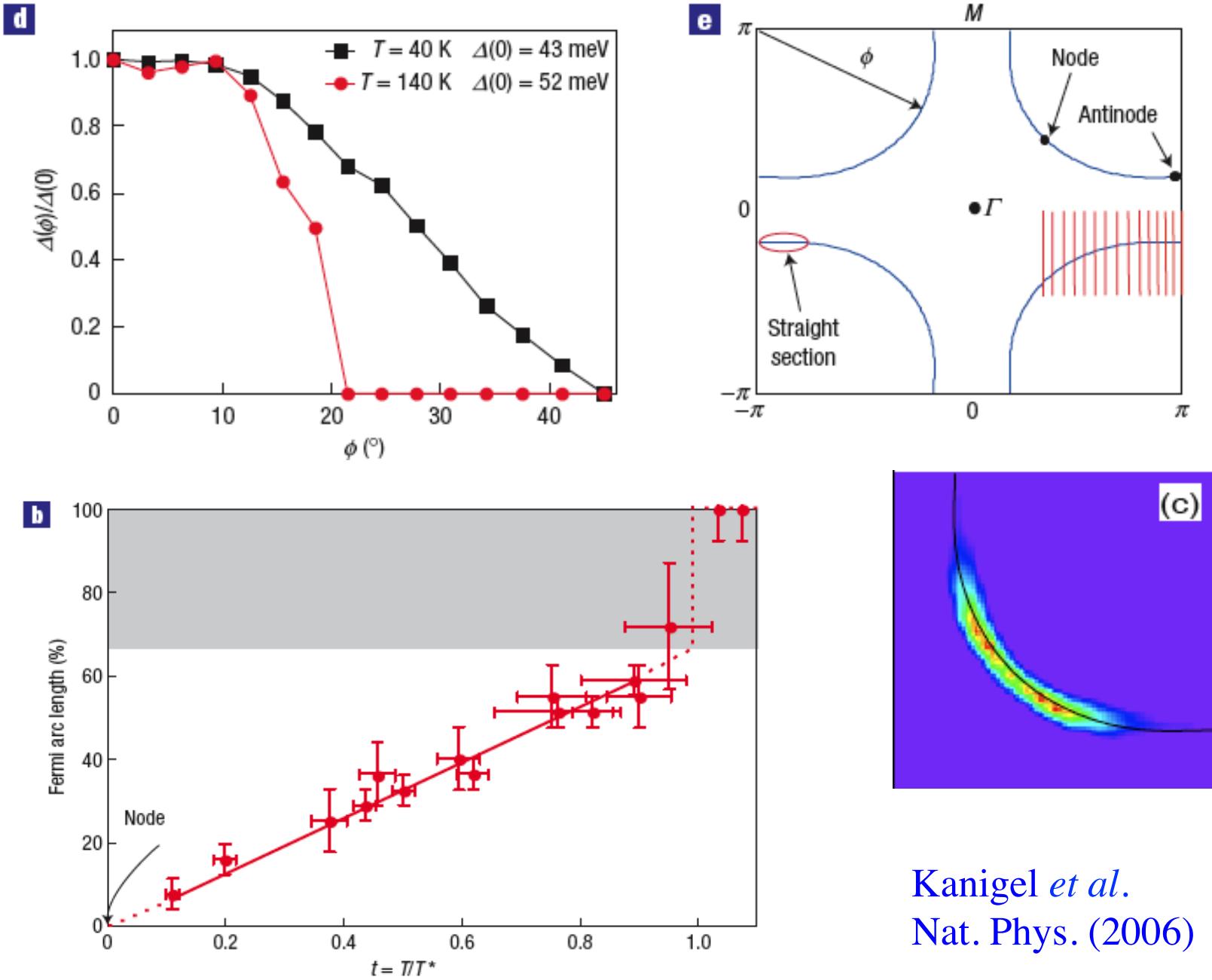


Relation of T^* to T_c

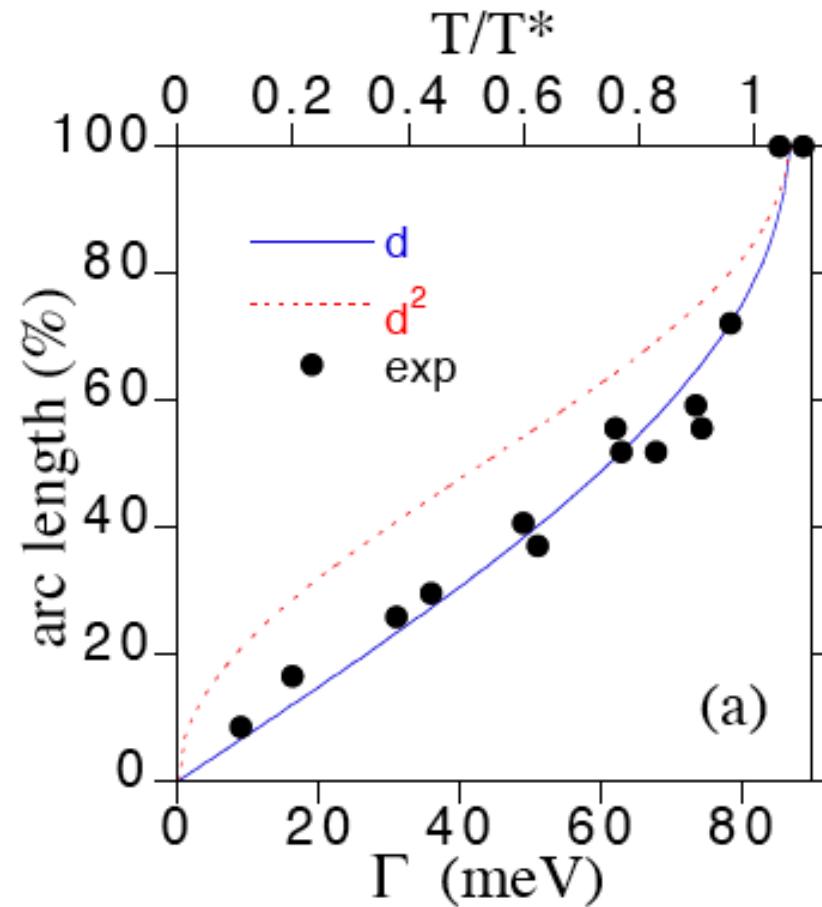




Is the T=0 limit of the pseudogap phase a nodal metal?



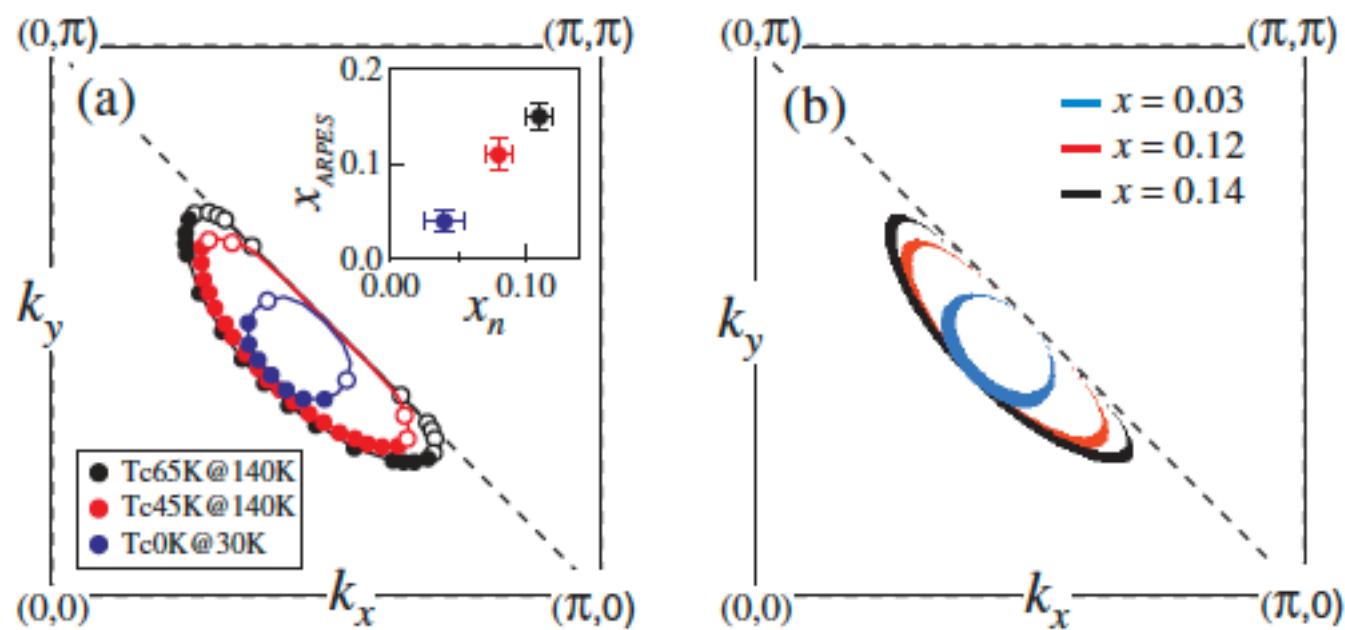
Arc Length is Linear in $\Gamma \rightarrow \Gamma \sim T \rightarrow$ Arc Length $\sim T$
(lifetime broadened d-wave node)



Also explains arc collapse below T_c ($\Gamma \rightarrow 0$)

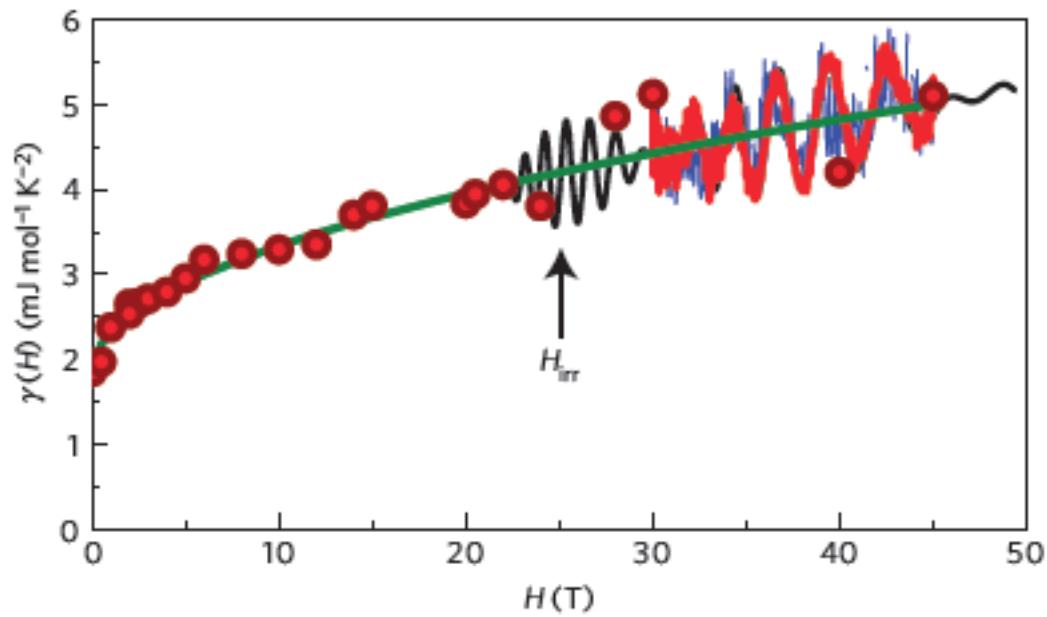
Norman *et al.*, PRB (2007)

Pockets instead?

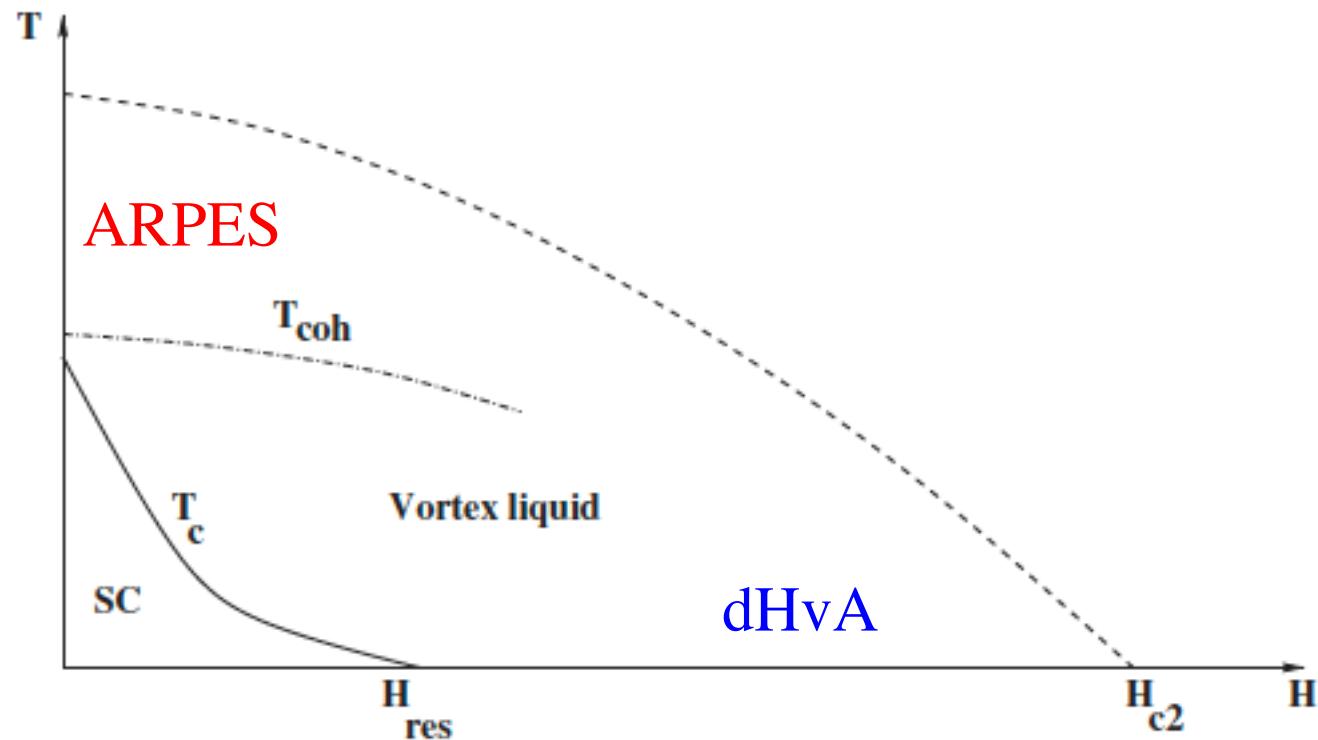


Yang *et al.*, PRL (2011)

Presence of small pockets indicated by quantum oscillations

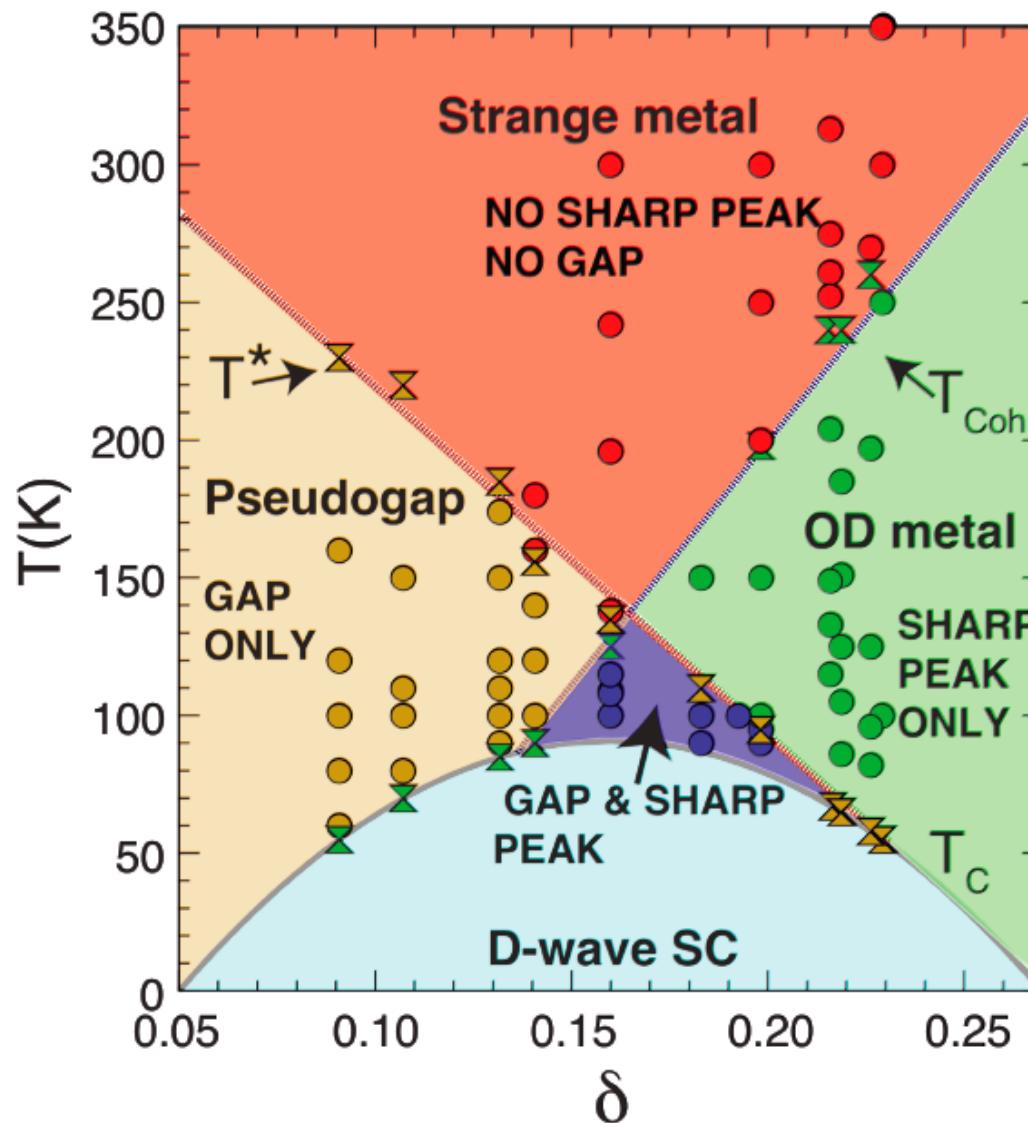


Riggs *et al.*, Nature Phys. (2011)



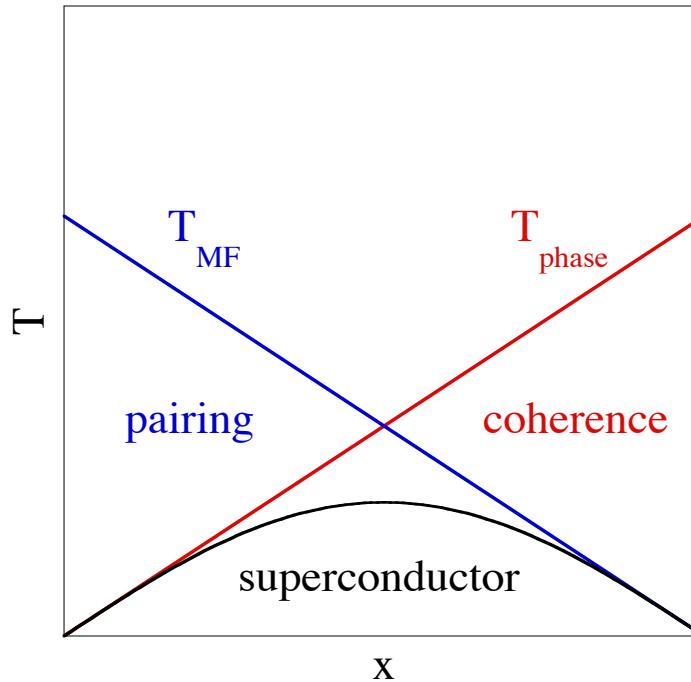
Senthil and Lee, PRB (2009)

Is it RVB?



Chatterjee *et al.*, PNAS (2011)

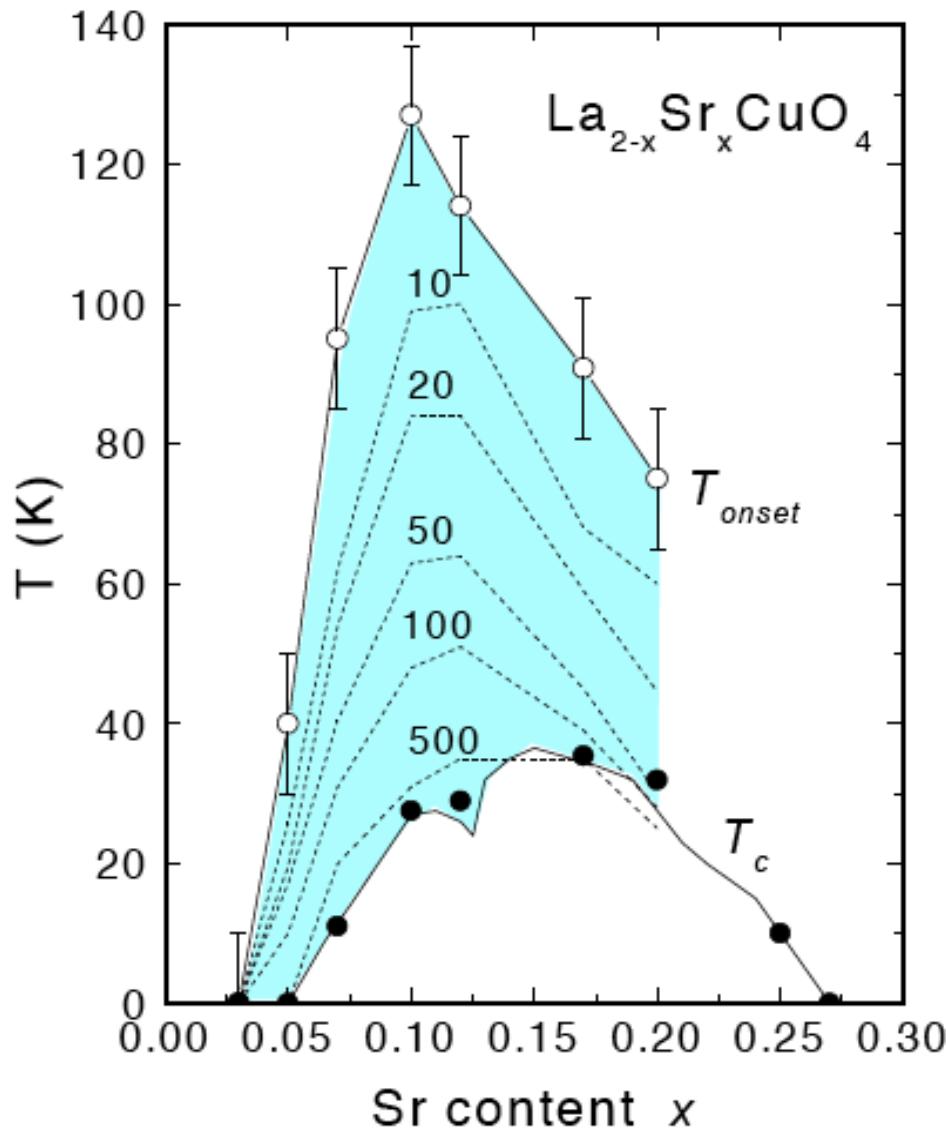
Phase Coherence for Pairs



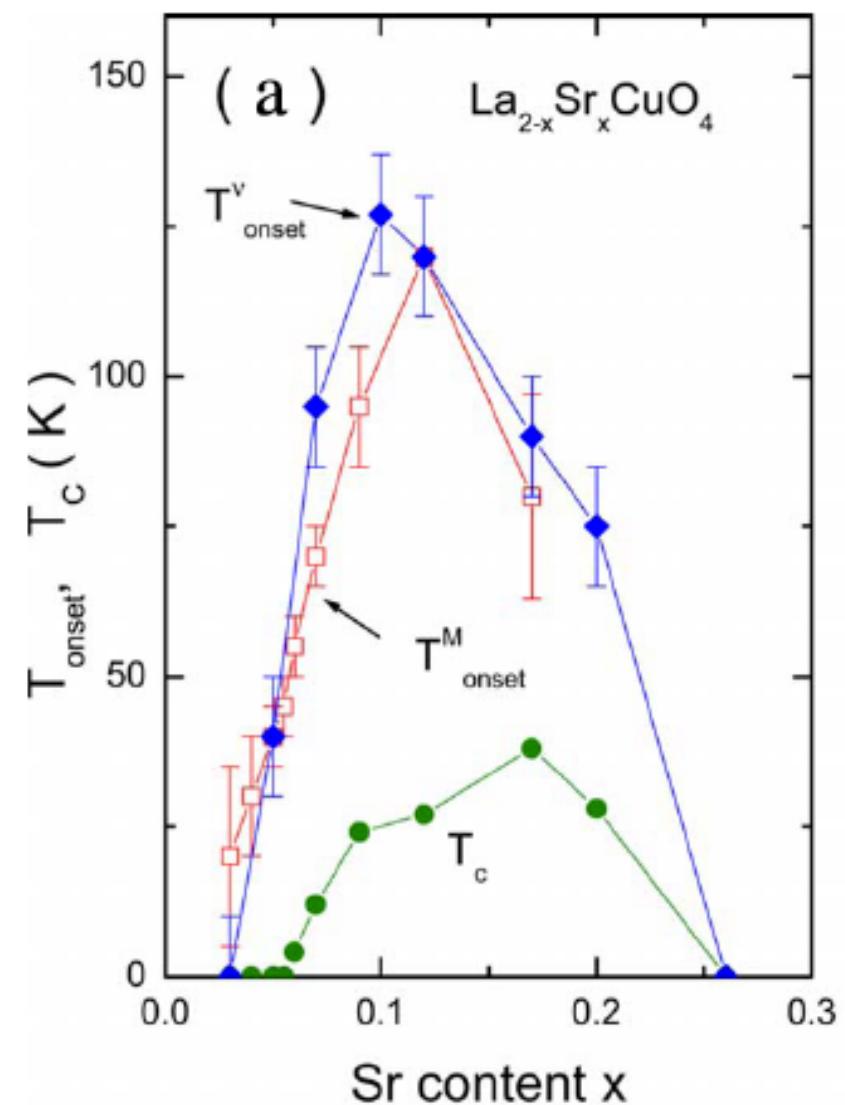
Pairing occurs below a mean field transition temperature
Coherence occurs below a phase ordering temperature
Superconductivity occurs only below both temperatures

Emery & Kivelson, Nature (1995)

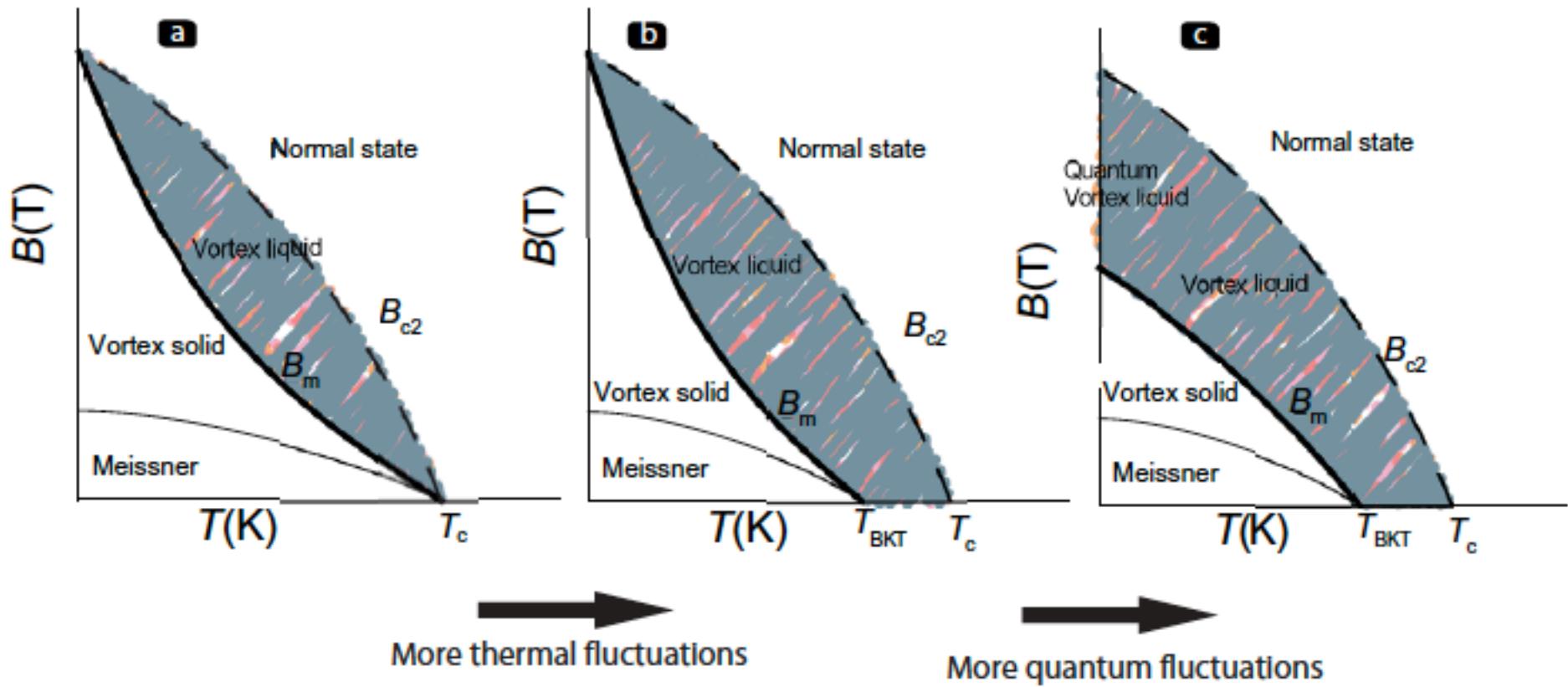
A large Nernst signal (due to fluctuating vortices?) appears above T_c



Wang *et al.*, PRB (2001)

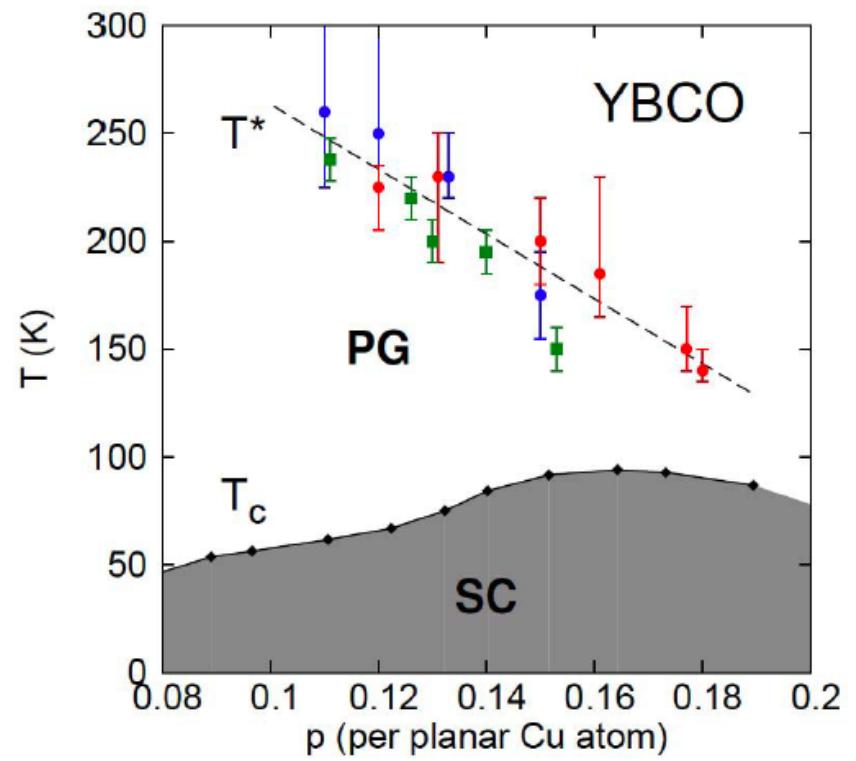
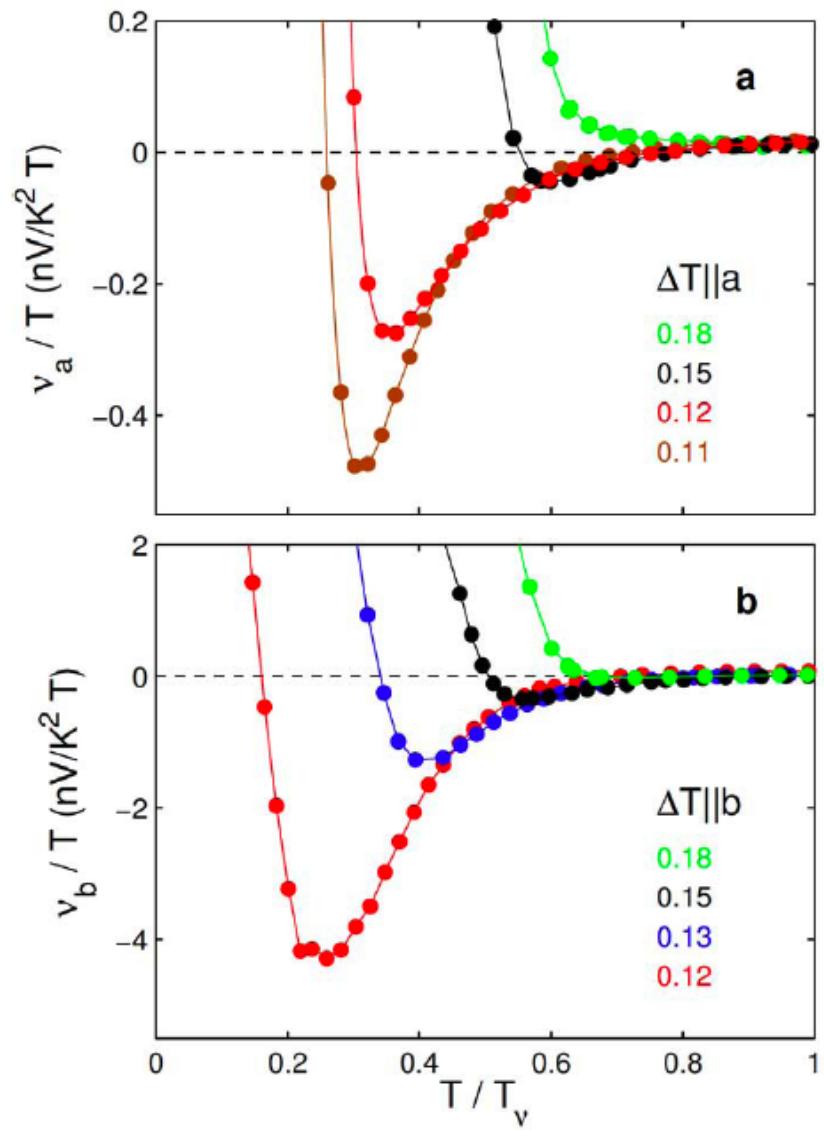


Li *et al.*, PRB (2010)



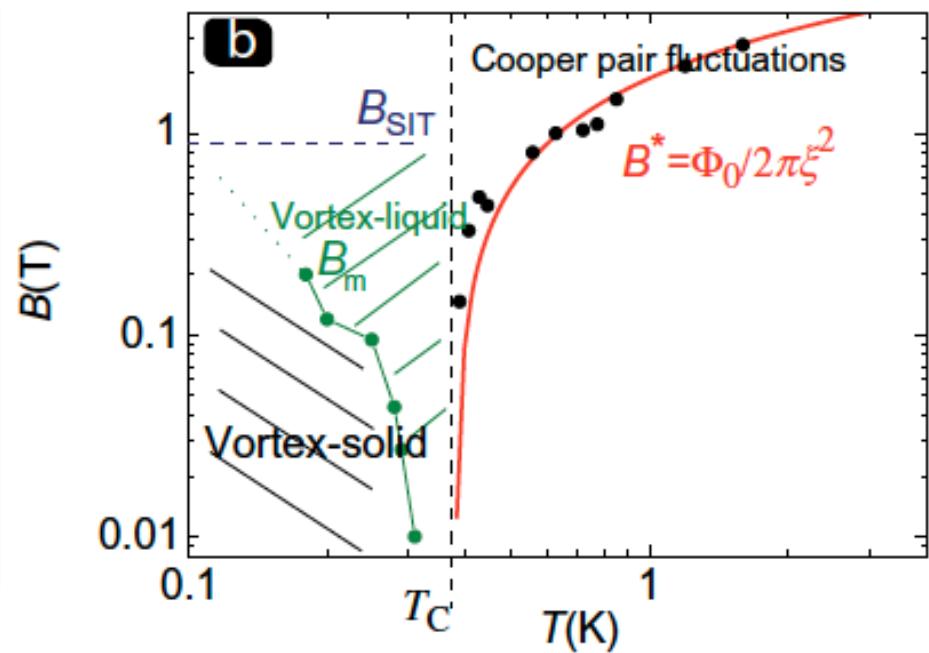
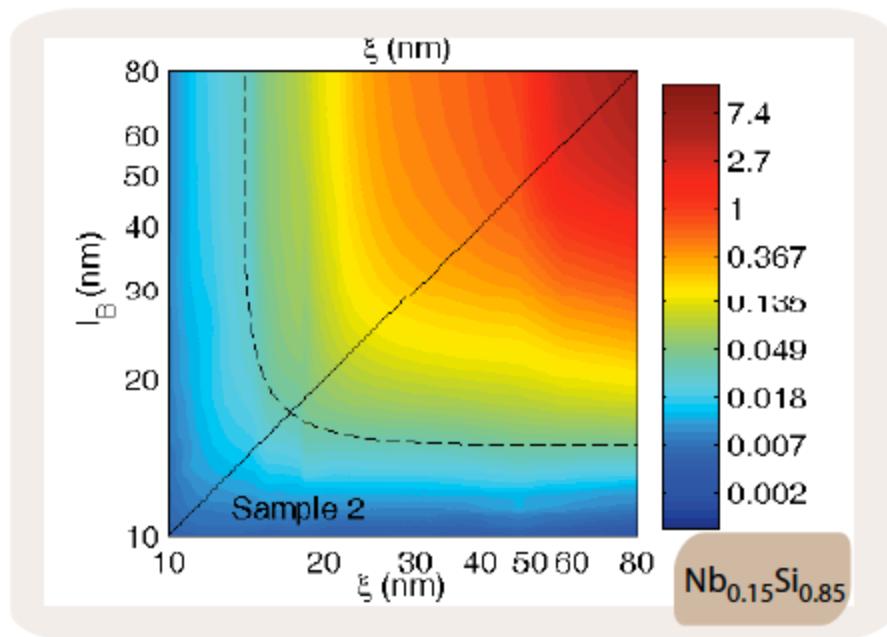
Pourret *et al.*, NJP (2009)

Anisotropic Nernst Signal below T^* ($a \neq b$)



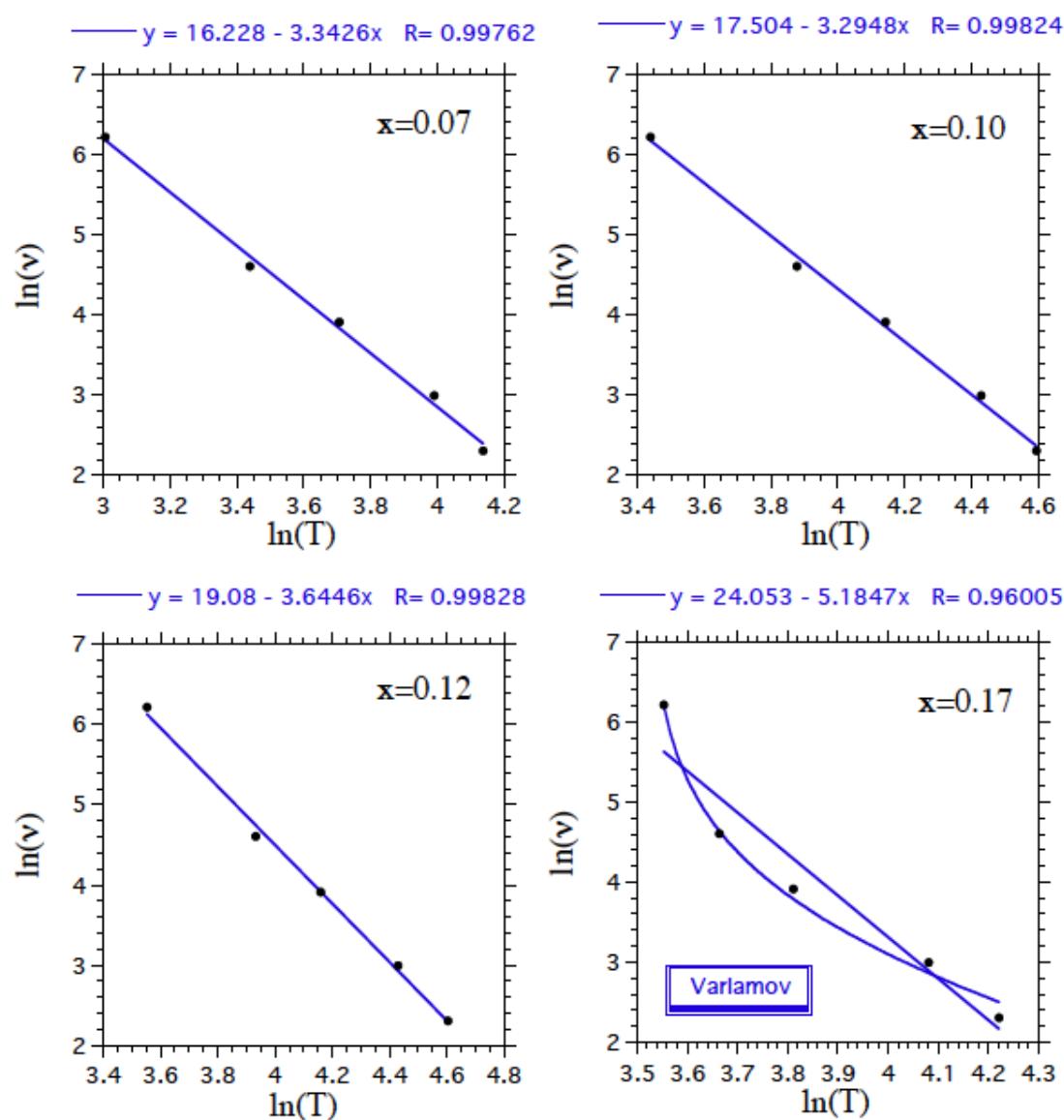
Daou *et al.*, Nature (2010)

Ghost Critical Field

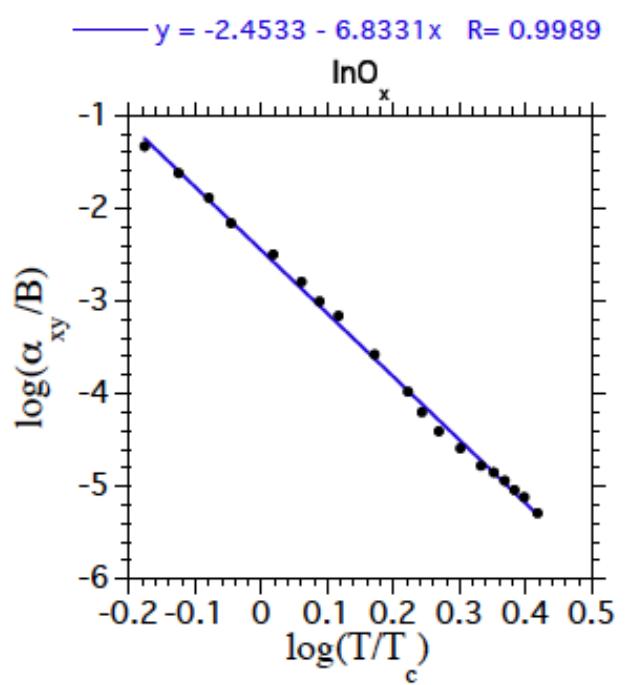


Pourret *et al.*, NJP (2009)

Nernst effect above T_c in LSCO



and in InO_x

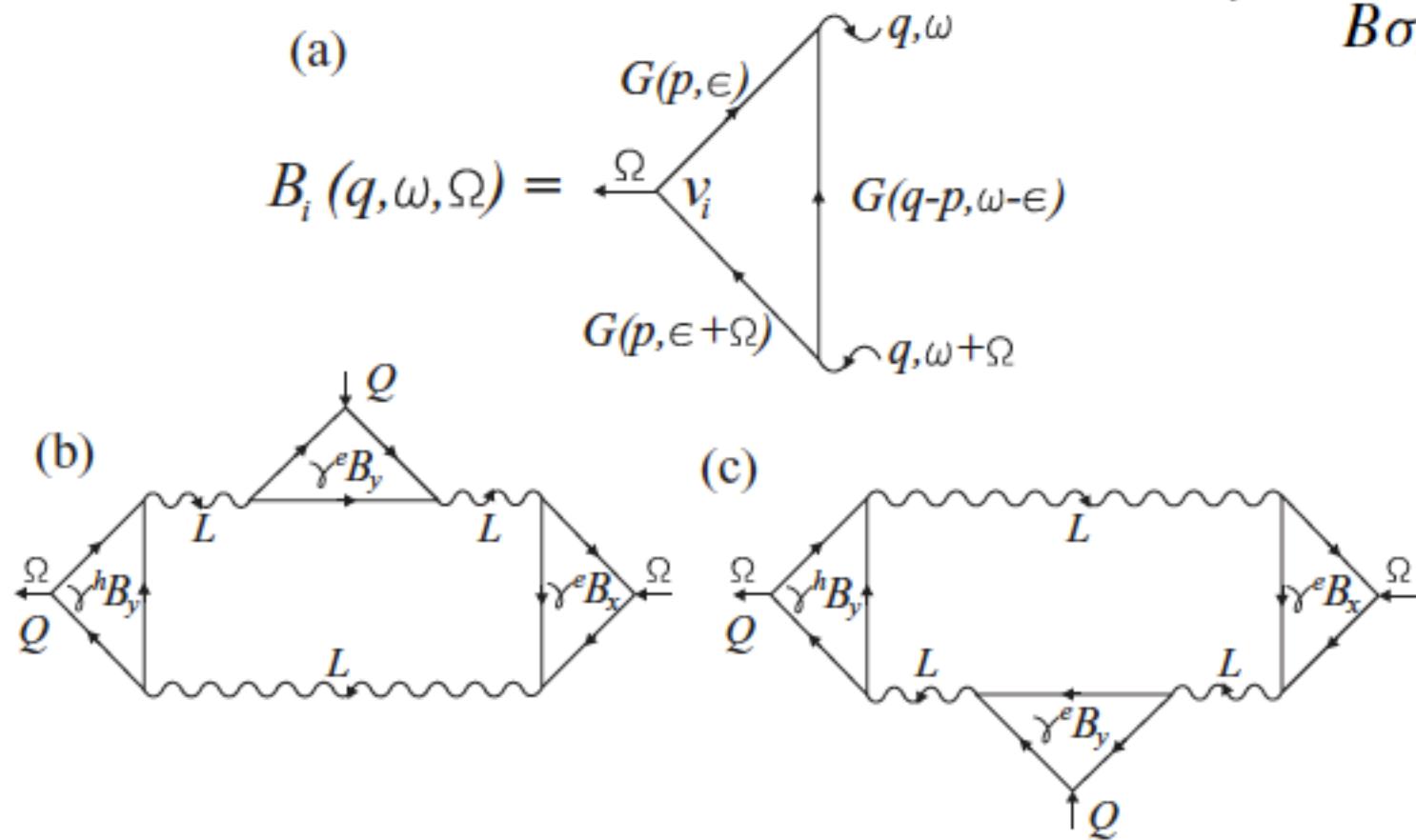


Pourret *et al.*, NJP (2009)

Nernst – Aslamazov-Larkin Contribution

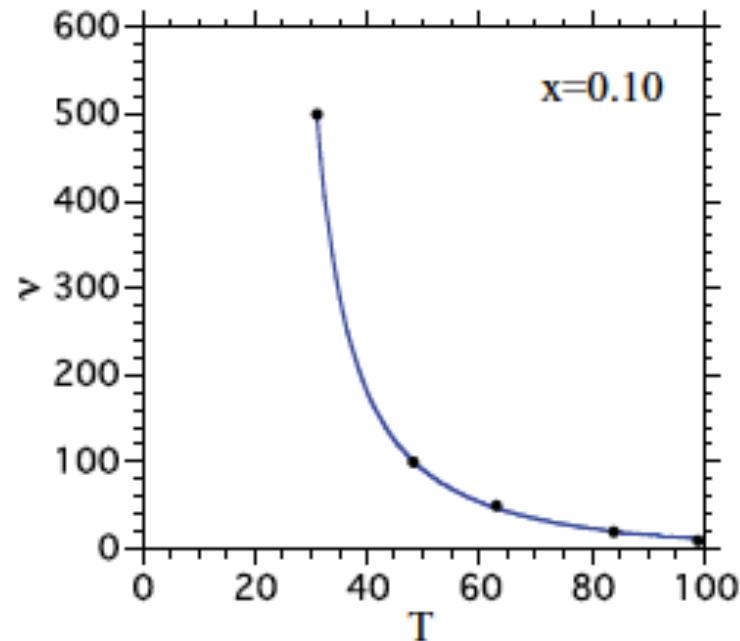
$$\begin{pmatrix} \mathbf{j}_e \\ \mathbf{j}_{th} \end{pmatrix} = \begin{pmatrix} \hat{\sigma} & \hat{\alpha} \\ \hat{\alpha} & \hat{\kappa} \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \nabla T \end{pmatrix}$$

$$\nu \approx \frac{\alpha_{xy}}{B\sigma_{xx}}$$



Levchenko *et al.*, Phys Rev B (2011)

Nernst – Correction to Gaussian Theory due to the Pseudogap

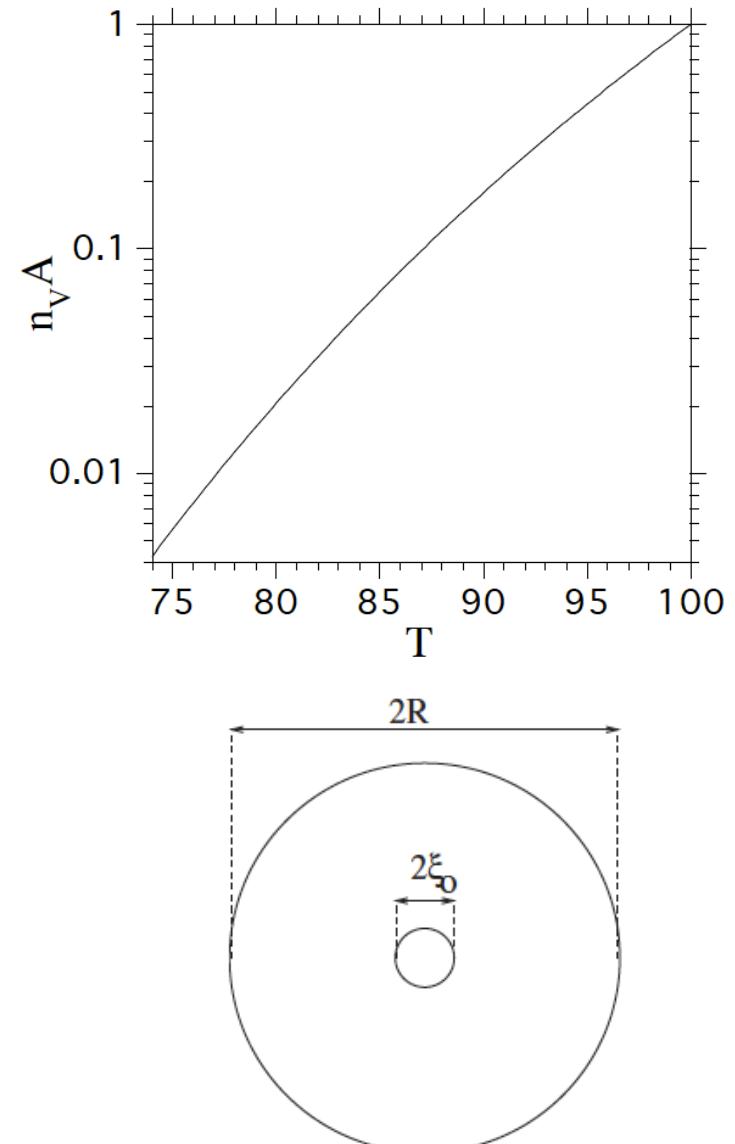
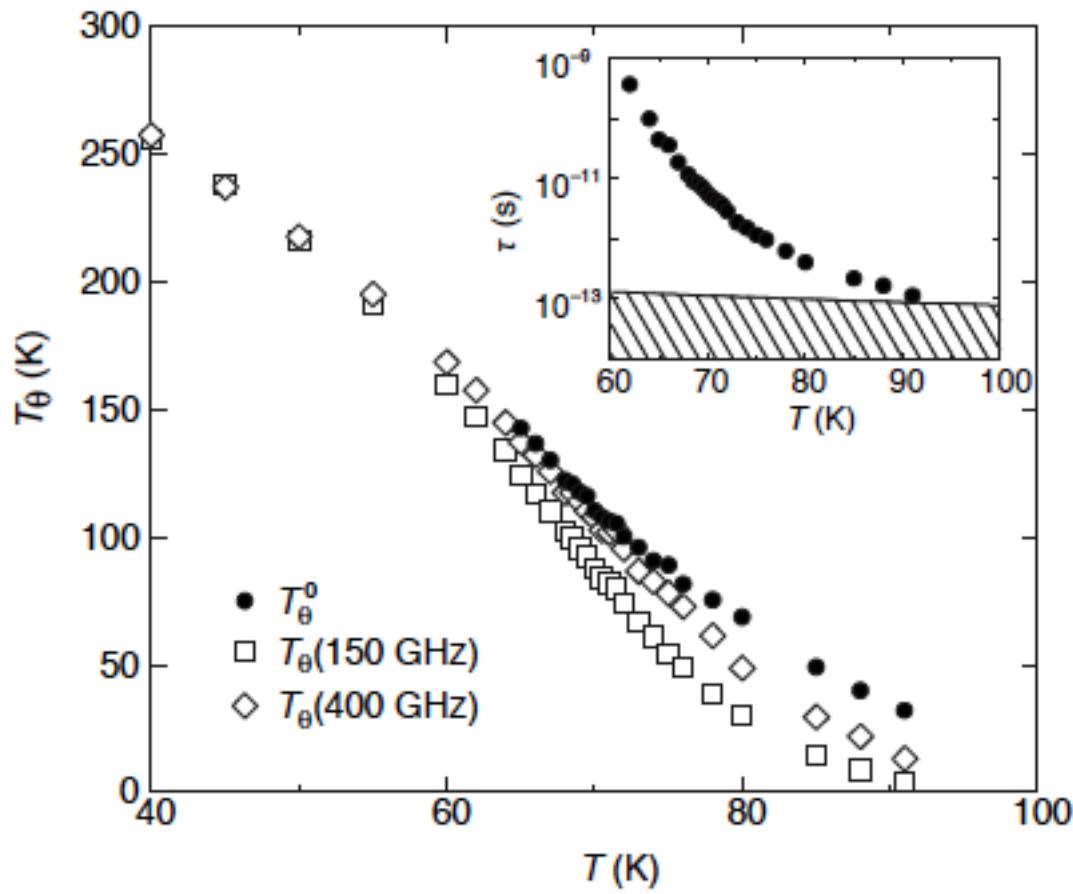


$$\bar{\alpha}_{xy}^{\text{AL}} = \frac{e}{2\pi\hbar} \frac{\xi_{\text{GL}}^2}{\ell_H^2} (B/B^G)^3$$

$$B/B^G = \frac{\pi^2}{24} \frac{\xi_0^2}{\eta} \left[\frac{(\Gamma/\Delta)^2 + 2}{(\Gamma/\Delta)\sqrt{(\Gamma/\Delta)^2 + 1}} - 1 \right]$$

Levchenko *et al.*, Phys Rev B (2011)

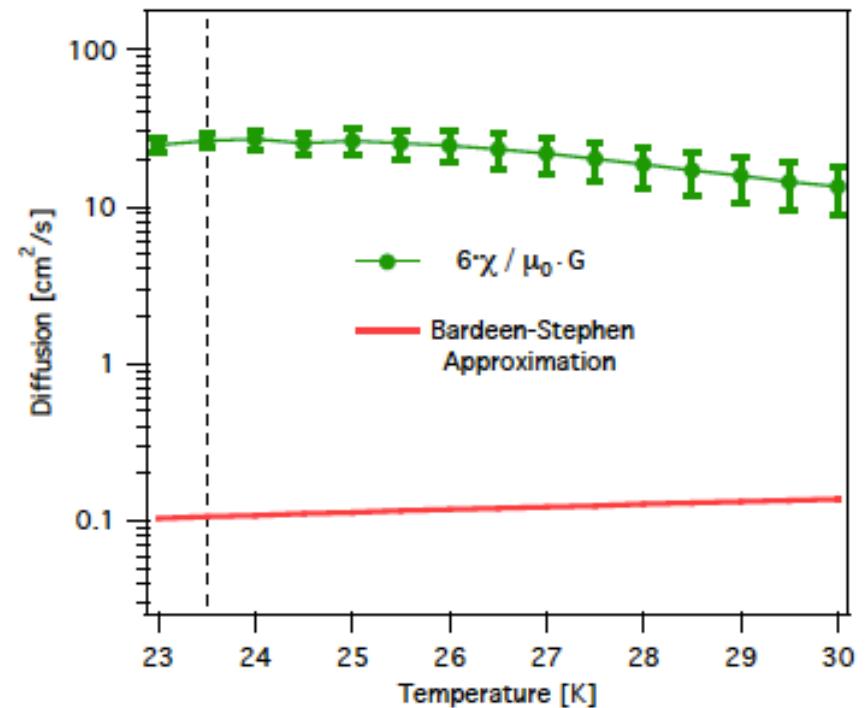
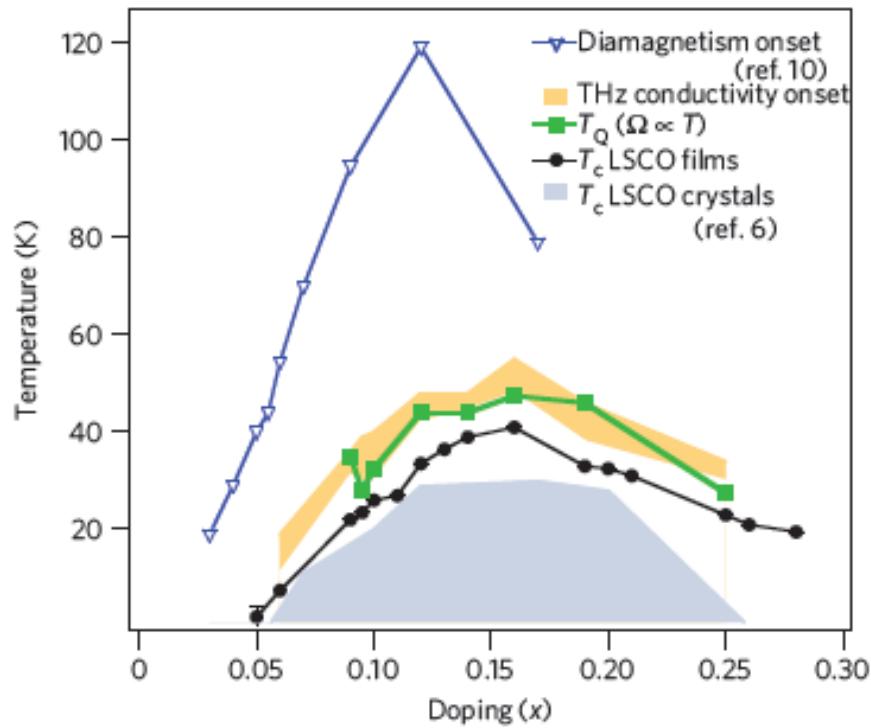
Terahertz conductivity – Evidence of “BKT” physics



Corson *et al.*, Nature (1999)

Orenstein *et al.*, Ann. Phys. (2006)

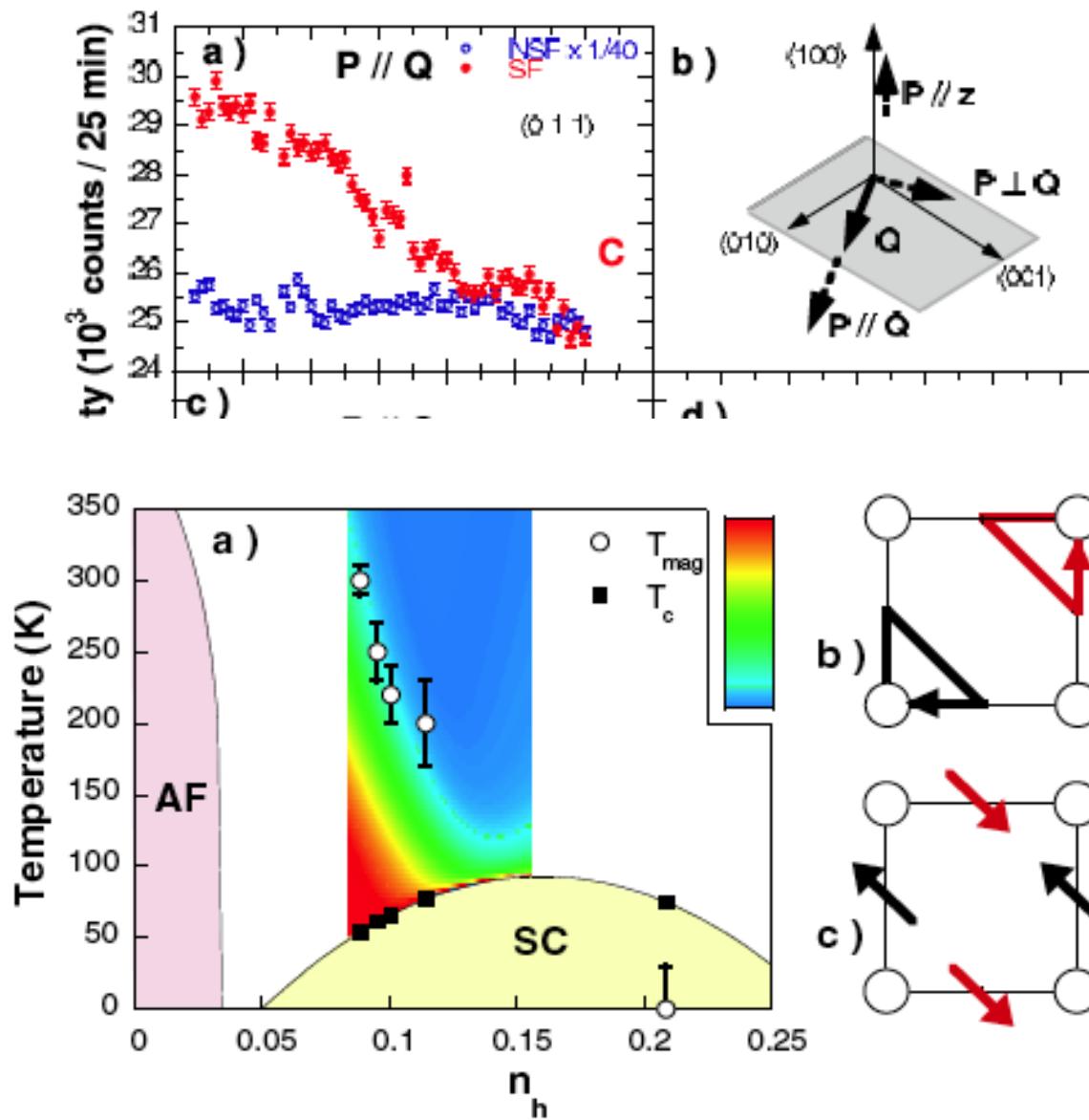
Terahertz conductivity vs Nernst and diamagnetism



Bilbro *et al.*, Nat. Phys. (2011)

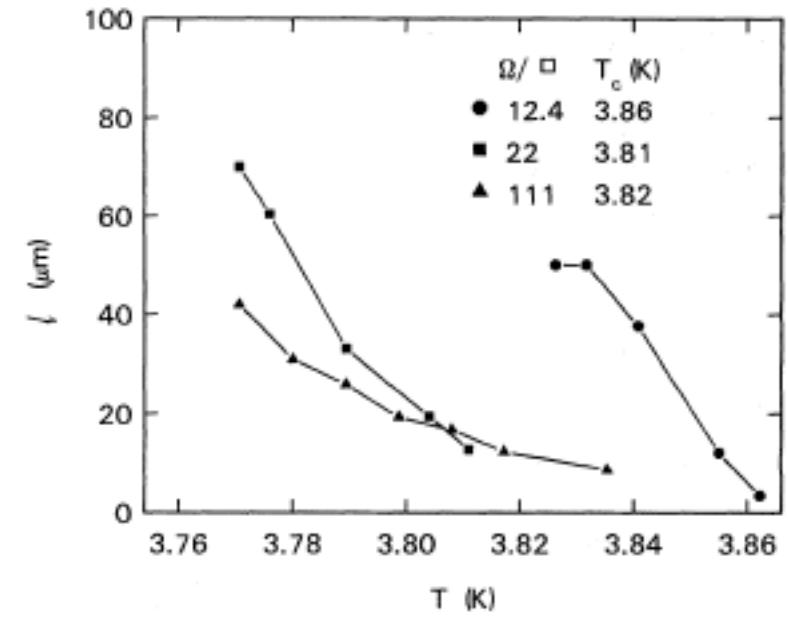
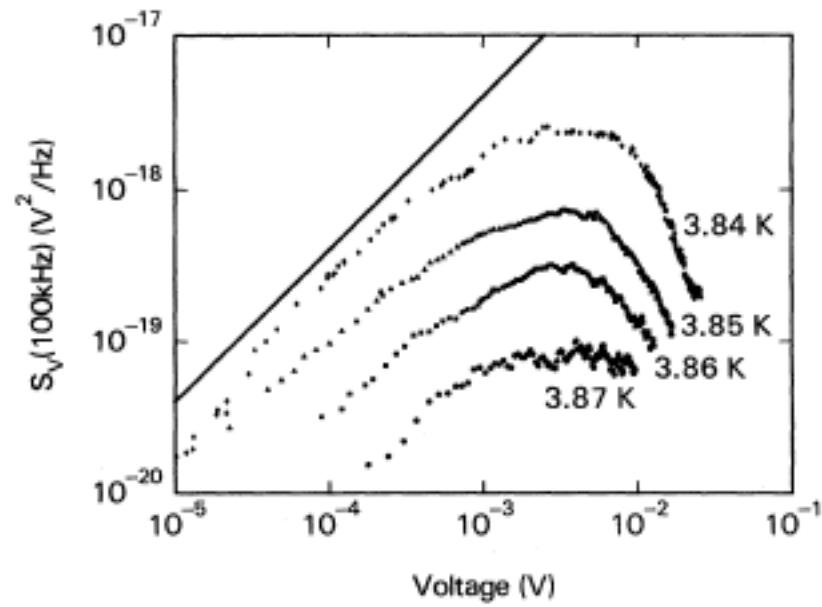
Bilbro *et al.*, PRB (2011)

Enhanced diamagnetism due to orbital moments above T_c ?



Fauque *et al.*, Phys Rev Lett (2006)

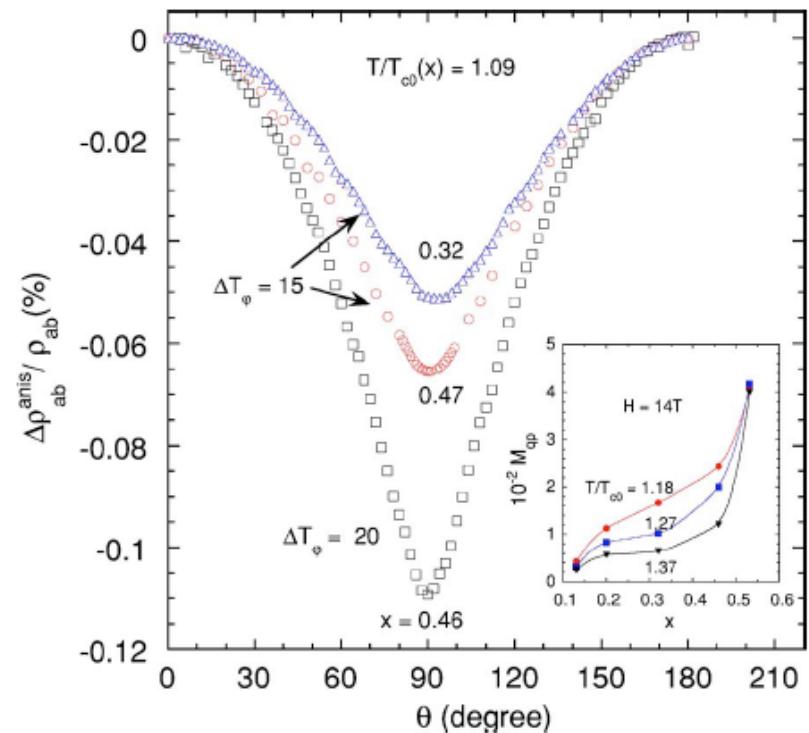
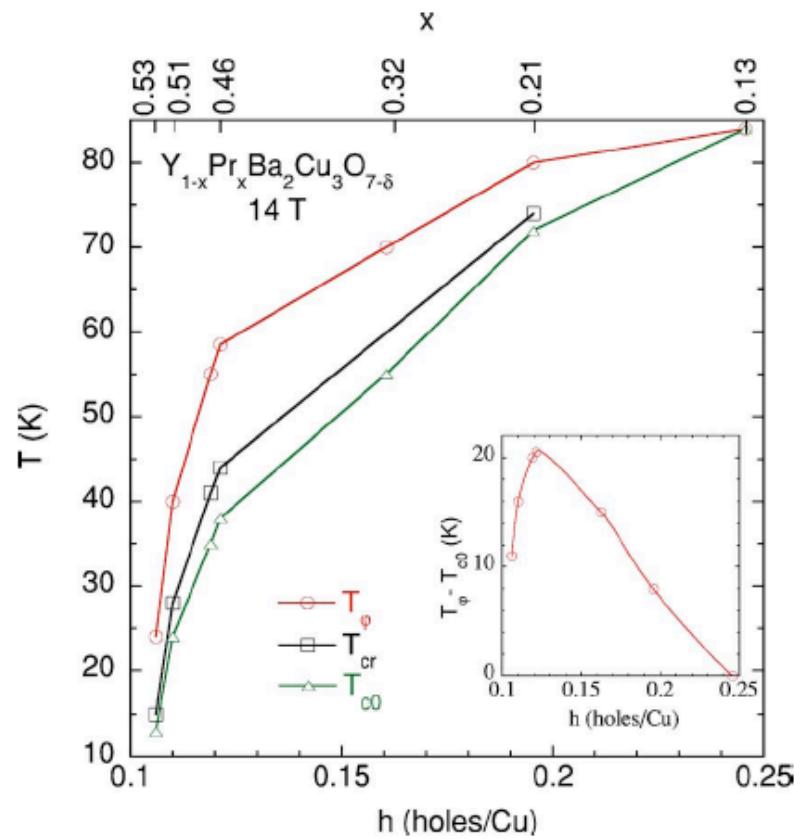
Voltage noise due to vortices



$$S_V(f) = 2\phi_0 \frac{l}{w} V_{\text{dc}}$$

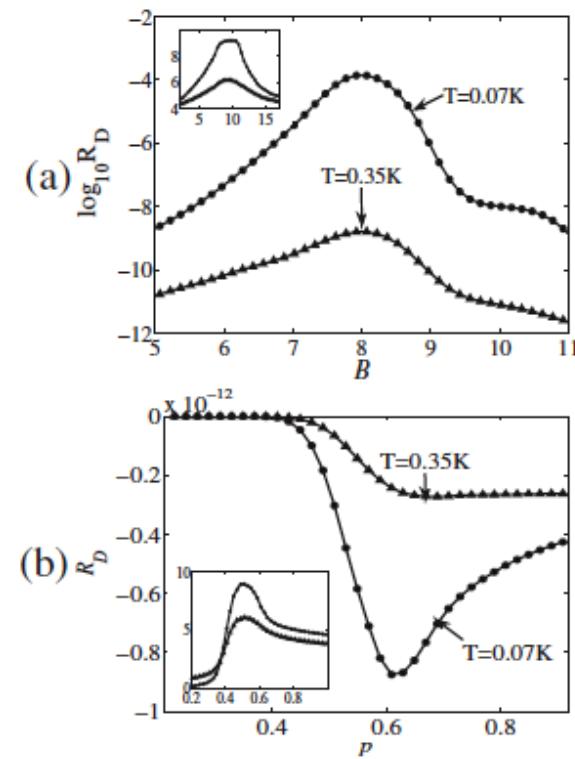
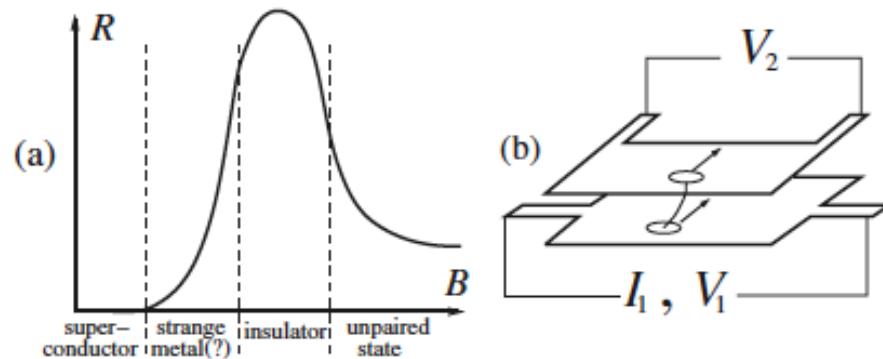
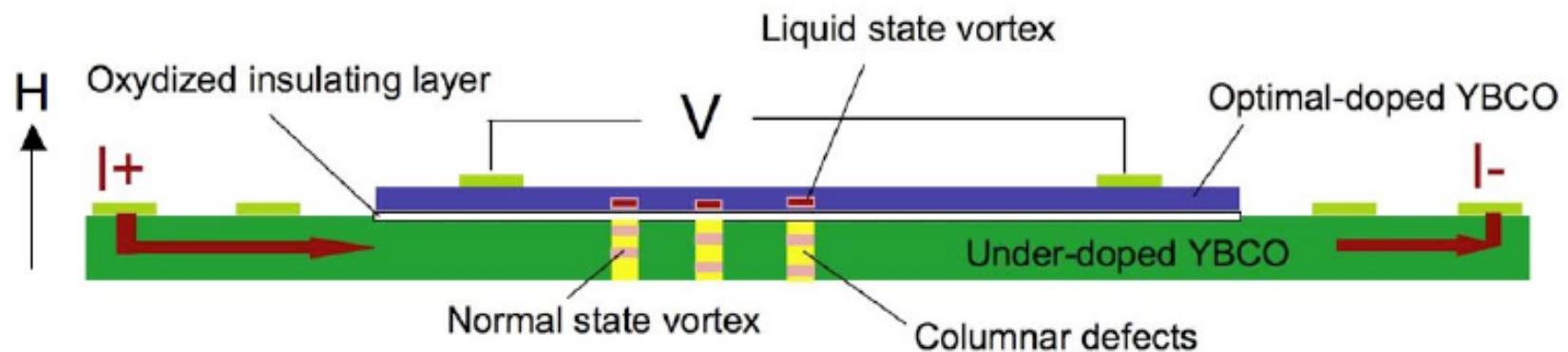
Knoedler and Voss, Phys Rev B (1982)

Angular magnetoresistance consistent with vortices above T_c



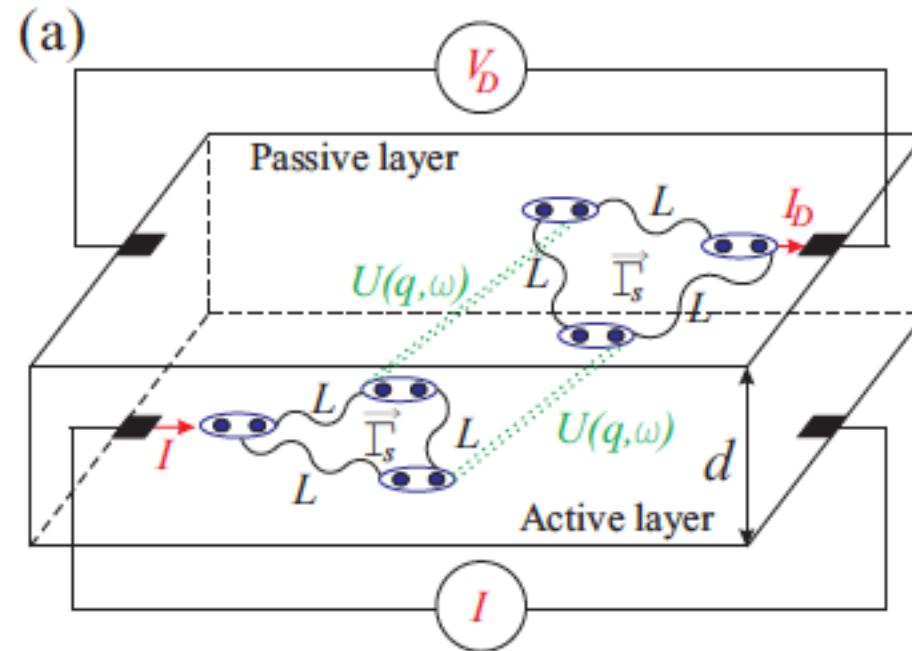
Katuwal *et al.*, Phys Rev B (2005)

Vortex Drag (Giaever transformer)



Zou, Refael, Yoon
Phys Rev B (2009 & 2010)

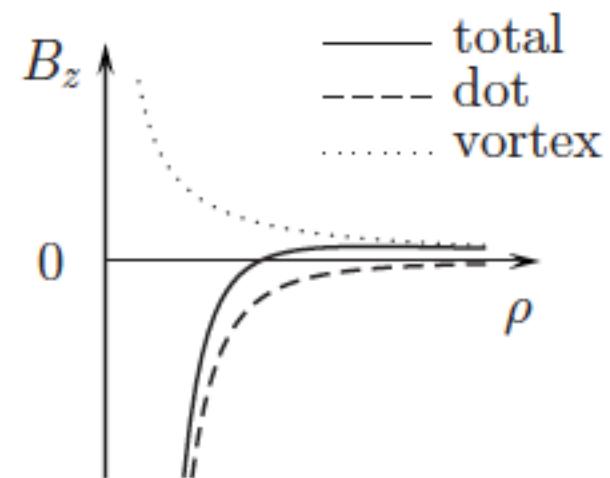
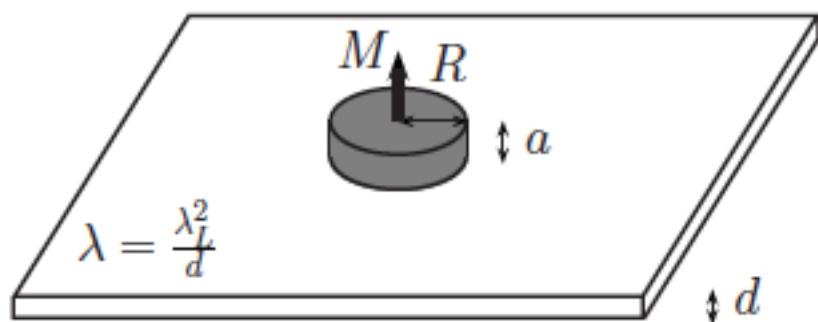
Drag is a sensitive probe of superconducting fluctuations



$$\frac{\sigma_D}{\sigma_Q} = \frac{15\zeta(5)r_s^2}{32} \frac{\partial\Delta_1}{\partial\varepsilon_F} \frac{\partial\Delta_2}{\partial\varepsilon_F} \frac{\lambda_{ss}(d)g(T)}{\ln^2 \frac{T}{T_{c1}} \ln^2 \frac{T}{T_{c2}} \left[\ln \frac{T}{T_{c1}} + \ln \frac{T}{T_{c2}} \right]}$$

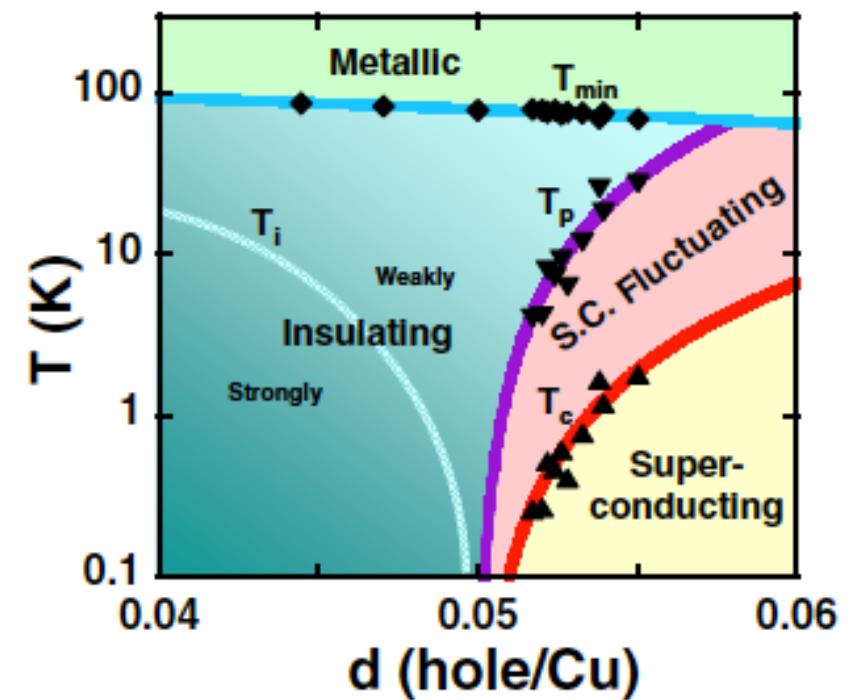
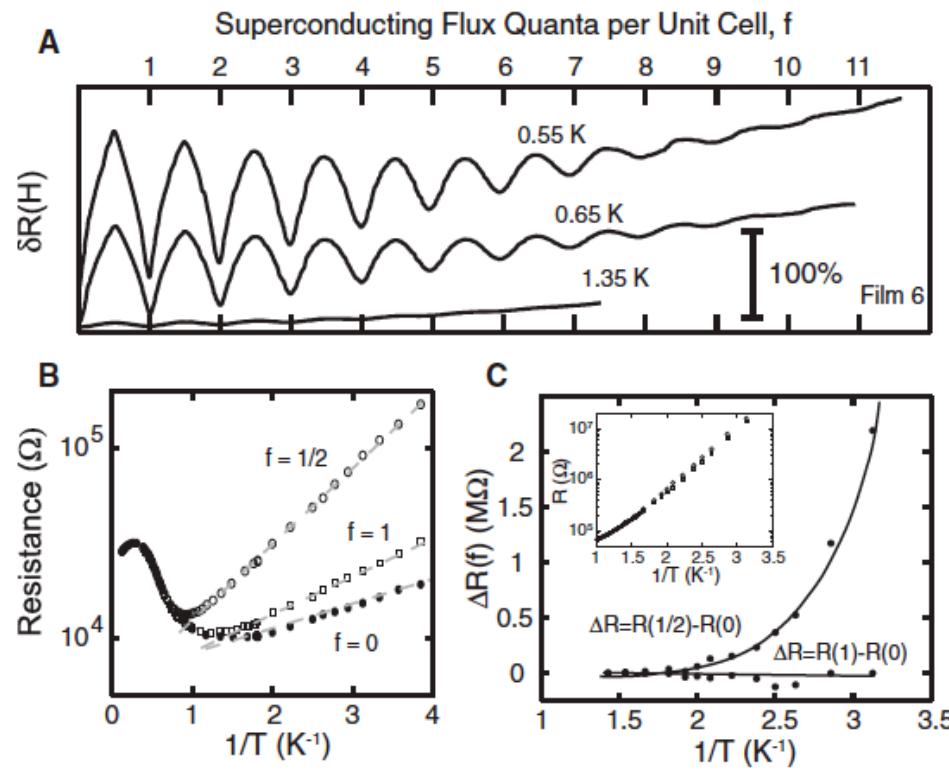
Levchenko & Norman, Phys Rev B (2011)

Trapping vortices above T_c



Ristivojevic & Norman, Phys Rev B (2010)

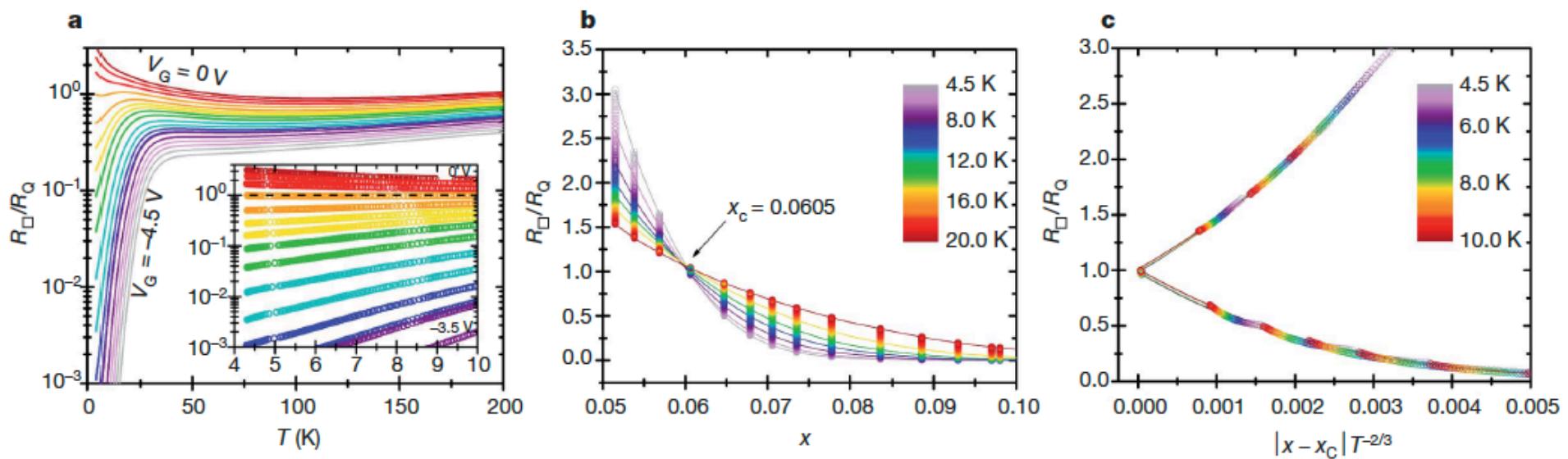
Magneto-resistance oscillations from patterned holes



Stewart, Yin, Xu, Valles
Science (2007)

Oh *et al.*, Phys Rev Lett (2006)

Superconductor-insulator scaling in LSCO with $R_Q \sim 2e$



Bollinger *et al.*, Nature (2011)

CONCLUSIONS

- Superconducting fluctuations do exist well above T_c but tend to follow a power law behavior
- The temperature range of “exponential” behavior as revealed by conductivity measurements is limited
- If pseudo-vortices do exist, they are likely limited to a narrow temperature regime above T_c
- Is the diamagnetism observed well above T_c due to pairs or orbital currents?